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The analysis of traffic control cyber-physical systems

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Abstract

Cyber-physical systems offer a new theory to the application of information to improve traffic control system performance. This paper, oriented to the integration of information and transportation processes, discusses the gateway role of the control instruction information of the information flow, control command, behavioral control utility and behavioral control and the reconstruction of the traffic control system model. Also, this paper analyzes the information flow amongst computer systems, traffic sign systems, and travelers in the traffic control system. The integration of information and transportation processes can be realized by cyberizing the traffic control process. Finally, this paper discusses the application of new technologies in computing and communication in the traffic control cyber-physical systems.

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1. Introduction

The road transportation system is a large-scale human-made engineering system. However, the road transportation system, only consisting of people, vehicles, and roads, cannot operate safely and efficiently. Traffic control technology, e.g. Intelligent Transportation System, can realize the traffic control by adding and installing a large amount of advanced electronic devices and information systems to the road traffic system, improving operational efficiency and safety level for the road traffic system. With the rapid expansion of the scale and the intensive usage of the traffic system, the traffic control system still faces enormous challenges, with which cannot simply dealt by adding advanced electronic devices and information systems. To achieve real-time perception and

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dynamic control of the system evolution and the traveler behavior to make traffic more safely, efficiently and economically is still one of the challenges in modern traffic control theory and technology in the large-scale road traffic system in which human is the principal part conscious activity.

Cyber-Physical Systems (CPS) (Lee, 2008; Lee, 2010) is the research direction for the revolution in the field of computing and information science. Although there are various definitions on CPS, according to the different disciplines and technology applications, no a definition has been widely accepted (Shi, et al., 2011; Liviu & Sanislav, 2011). In of the light of the discussion presented in this paper, the following definition on CPS has been adopted. CPS consists of the different types of large-scale infrastructures that have a large amount of information and physical components and have wide impacts on our society under their deployment. These systems include Energy Management System, Transportation System, Water Resource Monitoring and Control System, Logistics and Disaster Management, Pension System, and Intelligent Building System. To design such systems effectively, engineers need to improve the level of understanding on the interaction between information, physical components and users. Through computation, communication and control, the integration of physical and information processes for the large-scale human engineering systems was realized by CPS, making the systems efficient, safe, reliable, and creditable (He, 2010; Lee, 2008).

To achieve efficient and safe road transportation is one of the motivations to carry out the research on CPS and is one of the most challenging areas, as it possesses the information, physical and social features (Lee, 2008; Lee, 2010). The biggest difference between the power grid (Liu & Mu, 2012), the high-speed railway infrastructure (Zhu et al., 2011), communication networks (Lee, 2010; White et al., 2010) and other fields and the road traffic system is that the people are the key element in the road traffic system. All development and changes of the traffic system are caused by travel behavior of people. Therefore, the road traffic system cannot be simply described by the movement, and traffic control is also not the control problem of the movement of the objects, fluid or energy. This determines the problems that the Traffic cyber-physical system is facing is not only the integration of the physical process of the material and energy and information, but also the integration of information processes and behavior processes. Furthermore, in the traffic cyber-physical system, the information should have significant effect on the traveler behavior, when the interaction between physical systems and biological systems (people) is established by information flow, to realize information value. For the road traffic control, CPS studies elaborate, coordinated, efficient information space operations, realizing the traffic system control and travel behavior control (Shi, 2009) to make road traffic more safely and efficiently.

2. Traffic control and cyber-physical system

2.1. Traffic cyber-physical system

The road traffic system constructs a complex social scale of the physical world, which includes not only a large number of critical infrastructure that lives in natural-geographical environment and all kinds of man-made environment, such as, large bridges across the sea or rivers, long and big tunnels, high-risk sub-grade slope, urban elevated bridges, etc., but also massive variety of vehicles, people and goods in the complex road environment. Especially, in the urban traffic control system, there are a large number of electronic devices and information systems, as well as the complex management and control applications. We could decompose the applications of CPS in the traffic system and build road infrastructure cyber-physical systems, vehicle-road coordinated cyber-physical systems and traffic control cyber-physical systems, respectively. Functions and applications are shown in table 1.

This paper is devoted to the operational control of the road traffic system and discusses the traffic control cyber-physical systems, to integrate the process of information, the process of traffic systems, travel behavior deeply by computing, communicating, and controlling means to realize the safe and efficient transportation.

Table 1. Road traffic cyber-physical system

	Traffic physical process	Information process	Functions
Road infrastructure cyber-physical systems	The mechanics changing process of key transportation infrastructure like bridge, culvert, tunnel, subgrade, slope, roadside and so on	The ubiquitous sensing detection in a wide range of reliable interconnected. depth perception, forecast, warning and monitoring	To achieve real-time monitoring road facilities and transportation meteorological environment detection
Vehicle-road coordinated cyber-physical systems	The relation between the synergic relationship process of car-to-car and car-to-road which are running in the road and communication process	Wireless, high-speed, high-reliability, security communications, automatic driving safer and self-adaption	High speed information exchange, in order to guarantee the safety of vehicles in efficient access
Traffic control cyber-physical systems	The road traffic system process and the traffic control process	Traffic control system model description, traffic system control and traffic behavior control instruction optimization calculation	To achieve a more secure and efficient dynamic road traffic control

2.2. Reconstruction of the road traffic control system

CPS is not about the application methods of advanced information technology, but about the theory constructing new systems by integration of information processes and physical processes. Therefore, the research of traffic control physical systems start from the re-analysis of the model and construction.

First, CPS builds an effective paradigm in order to use the information elaboratively, coordinately and efficiently and make it works, and this can make the traffic control not only facing to the operation of the traffic system, but also facing to people and their behavior in the traffic system directly. In the model of traffic control cyber-physical systems, there is no need in traffic control cyber-physical systems to continue to assume travelers as "robots" performing traffic control instructions, or simplify travel behaviors as the movement described by the probability.

Second, in the traffic control model, we cannot separate the three types of information in the traffic system: the electronic information in the computer and network, the information shown on the traffic facilities and the information involved in traveler's cognition, decision and implementation to facilitate the traffic behavior. Thus, the traffic information includes all information involved in the process to achieve the traffic control objective, whatever systems, materials, or energy they rely on and in whichever ways they are presented, obtained, stored, transmitted, and processed. The traffic control system exists for information.

Third, from the technology applied so far, it is evident that all traffic controls have been realized by using traffic behavior control, to achieve the control purpose. Travel behavior is an impassable gateway for the information flow in traffic control. Traffic behavior, road traffic behavior, vehicle driving behavior and slow traffic behavior convert the information of various traffic control instructions into the motion forms of the road traffic system.

Fourth, traffic behavior is a kind of social behavior, including the individual and group behavior. Related scientific research and experiments show that social behavior is controllable, and information is the main means of behavioral control. According to the system purpose of traffic control, the information of configuration, scheduling and deployment can realize the control of traffic behavior (Shi, 2009; Shi & Chang, 2008)

Figure 1 shows the model of traffic control system and traffic control information flow in control system.

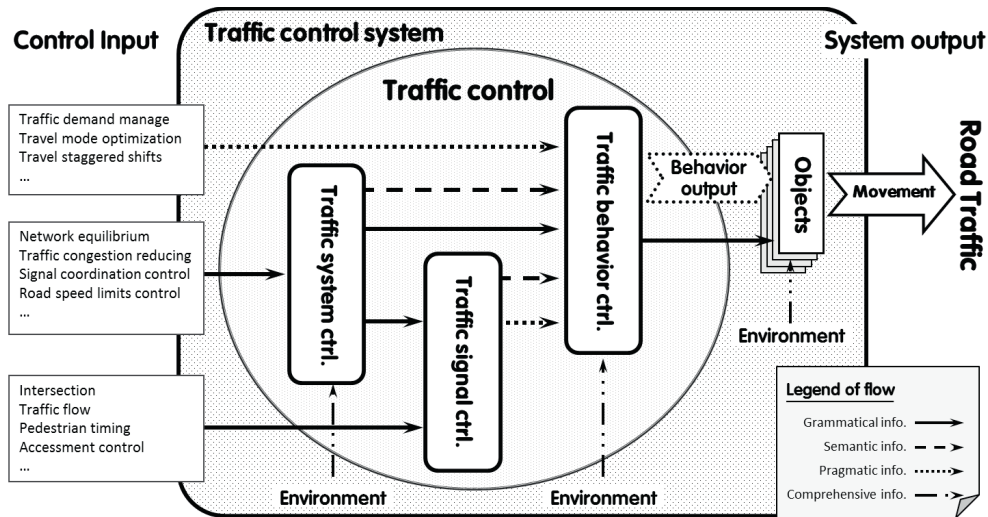


Fig. 1. Reconstruction model of traffic control system

2.3. Traffic control cyber-physical systems

The traffic control system is one of the most complex systems in the cyber-physical systems research. Some studies has attempted to apply CPS to the analysis and design of ITS, traffic control and guidance systems.

An effective traffic control cyber-physical system should be built on the basis of the traffic control system analysis and the design of the characteristics of information systems. It is composed of three levels, the application of the CPS theory of integrating information process into transportation process, traffic detection and control of information on the implementation of technical solutions and support of modern computing, communication and control technology, as shown in Figure 2.

An effective mapping should be constructed for the road traffic system in cyberspace to facilitate the traffic control objective, i.e. to establish traffic control system model and model parameter sets. The final results from the computation of the model-based, data-driven information space are eventually published by a set of information and consequently control is realized for the road traffic system.

The sensor collects real-time data for the traffic control system and processes (we can also find movement and behavior rules by calculating), driving the control computation, setting traffic control devices and implementing control of the traffic system and traffic behavior.

The computing, communication and control technologies serving to traffic control should be sufficiently applied and developed, and information should be applied to travelers and other devices elaborative, coordinately, and efficiently.

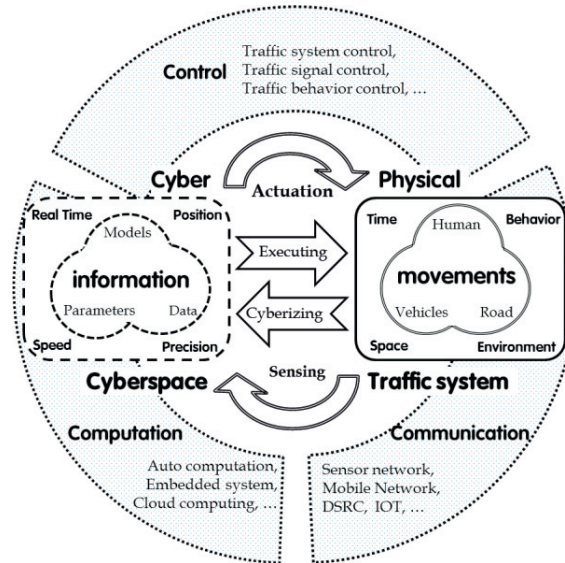


Fig. 2. Fusion model of information process and transportation process

3. Cyberizing the traffic control system

The approach to modeling and designing cyber-physical systems is to “cyberize the physical” (CTP), which means wrapping software abstractions around physical subsystems. The existing illustration for this approach wraps the physical measurements of a sensor network in database abstractions (Gong & Li, 2012). Actually the challenge of integrating computing and physical processes has been recognized for some time, motivating the emergence of hybrid systems theories (Madden et al., 2002).

For the traffic control system, cyberization is not based on sensor network, database and software to realize data acquisition, processing and description of the road traffic system. The model of the traffic control system, as shown in figure 1, needs to be oriented to comprehensive information and establish a complete mapping for the traffic physical system, process and behavior in the cyberspace.

3.1. Information in traffic control system

Information is usually considered as a definition of the content that is exchanged between the outside world and human during the process of adapting to the outside world and controlling the outside world. For the road transportation control system, the information flows between different forms of elements, which are composed in the control system: computing and communication systems, traffic information devices and travelers. Therefore, the concept of traffic information includes three different kinds of information, as showed in table 2. The first kind of information is the electronic information which exists in the traffic computer system and communication network. The second is the management control information which is oriented to travelers. The last is the behavioral decision information which is acquired by travelers (pedestrians, drivers) and has an effect on the travelers’ behavior.

From the reconstructed model of traffic control system, it could be concluded that all traffic control can be realized only through traffic behavior control. From this perspective, the ultimate objective of all the traffic information is to serve, affect and control the groups and individuals’ traffic behavior. Consequently, the key

feature of the traffic control cyber-physical systems is oriented to the traffic behavior and realizing refined, coordinated and efficient information computing, communication and control among the electronic systems, traffic signs and travelers.

Table 2. The information classification based on information flow and carriers

Classification	Carrier	information form	Description
Electronic information (expressed as syntactic information)	Communication system, computer, control device	Traffic video, audio, image	Traffic operation video, traffic accident scene and data which is acquired by electronic device; the record of traffic data system acquisition system.
		Traffic data	All kinds of traffic data and reports, the historical data of the operation of traffic system and the Statistical and analytical data at detection point
		Geographic maps	Basic geographic information, TGIS, information of GPS
		Others	Traffic control model and its parameters, the results of traffic simulation and the deduction, computer systems and network security records
Management control information (expressed by semantic information)	Traffic information expression device	The number and text of traffic signs	The number of exit and entrance, road name, etc.
		Traffic pattern	Warning pictures, etc.
		Voice, sound	Road transportation broadcast information, ect.
		Light	Signal light, turn signal of vehicle, ect.
Behavioral decision information (presented as pragmatic information)	Human(traveler)	Traffic information traffic needed	Traffic information about management, guidance, prompting, ect.
		Acquired traffic information	Traffic information which is cognized correctly
		Traffic information which influence behavior	Information that has an effect on traffic behavior
		Traffic information issued by individuals	Traffic prompt message given by travelers

3.2. Cyberization of the traffic control system and its process

To achieve the integration of traffic physical process and traffic control cyber process, the first step is to realize transportation system and its process cyberizing. The primary state of constructing traffic control cyber-physical systems is to cyberize the traffic control system.

The core to cyberize the traffic control system and its process is computation. The development in computer science changes the status of the computation thoroughly: computation has become the third scientific form following the theory and practice (Zhong, 2007). The foundations of computer which is pioneered by Turing, Church and Von Neumann, are about the transformation of information, not about physical dynamics. In the research of CPS, computation expresses two concepts: the one is that computation is an effective method of scientific research and experiment analysis for CPS, and the other to depend on and realize the processing process

of control information by information communication network during the CPS operation, which is generally referred to as “automatic computation”. Figure 3 shows the details of cyberizing the traffic control cyber-physical systems.

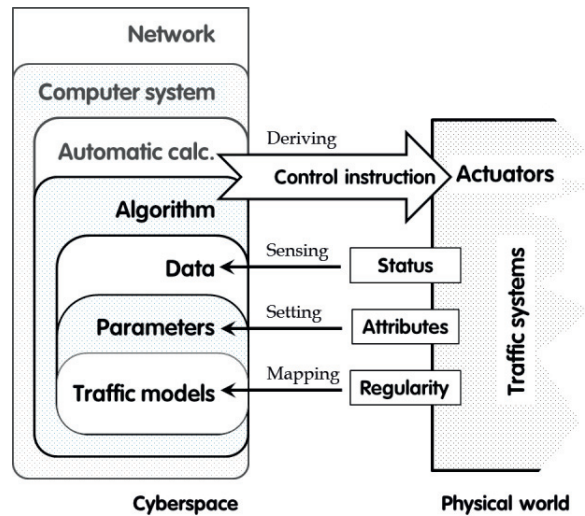


Fig. 3. The details of the cyberization of the road traffic control system

The core of cyberization is the construction of descriptive model for the traffic control system in cyberspace, and the construction of description model facing the problem of the modeling of the road transportation system and complex behavior. Many researchers have been focused on road transportation system modeling, while the difficulty is complex behavior modeling. It cannot be compared between transportation science and physics science. It is difficult for studying of traffic behavior through model, and the model cannot be determined in one step. It always from the direct simulation of superficial and visible transport phenomena to active modeling with certain theoretical basis gradually (Huang, 2002; Huang, 2005). Researchers have been conducting a lot of researches, which include describing the law of road transportation control system, such as applying hybrid system theory to establish the traffic control model (Madden et al., 2002; Zhang et al., 2004; Jiang et al., 2009), the traffic multi-agent system model (Ou et al., 2000), the social cluster behavior control and the traffic flow forecasting model, ect.

Real-time detecting the operation of transportation system, collecting and processing dynamic data is the foundation of computation, based on traffic model to realize control objectives. According to control requirements, traffic control cyber-physical systems need to acquire the status of road transportation system, the motion parameters and traffic group behavior and individual behavior parameters. The detection and data processing about the traffic behavior is more difficult.

The actuation of traffic control instructions and the construction of control instruction information. Signal control is an effective control means for the traffic control. Superficially, traffic signal control is a typical control model that machines control people. However, the device of signal lights is just a carrier of control instructions information. Actually, the device of signal lights is a device to release the traffic behavior control instructions information, and not the actuator in terms of automation. Constructing cyberspace of control order for changing or controlling traffic behavior can be considered as the executive process of traffic control cyber-physical systems, and is also the key content of cyberization in the traffic control system.

4. The physical implementation of the traffic system computation

The development of IT provides strong support to build cyberspace that adapts with traffic scale and it also provides solutions to achieve information detection, calculation, interconnection and execution of traffic control CPS, which makes cyber having the substance foundation.

The sensor network is an important support technology to the CPS, it contains the all nodes in interconnected sensors network, and there are two major existing systems of data exchange of nodes that is wired means and wireless means. The sensor node is consisted of sensor, data that can be detected and processing, executive component. The sensor is a converter that measures a physical quantity and converts it into a signal which can be read by an observer or by an (today mostly electronic) instrument. Compared with other networks, sensor networks have own characteristics, such as energy-limited, ad-hoc, strongly dynamic, related to the application level, data-centric(Ma & Tao, 2006). With the interconnected personal phone device, the floating vehicle network equipped with GPS, the road detection and so on, traffic sensor network can extract and analyze rules of traffic behavior (Froehlich et al., 2009; Rose, 2006).

The Internet of Things provides a kind of technology method that make various moving vehicles, goods, and all kinds of traffic control devices connected together in traffic control system. The technology makes information effectively interaction (Atzori, et al., 2010; Sun et al., 2010).

The embedded system provides a miniaturized computer system, suitable for large traffic control system which has a field of real-time computing requirements calculated. In the traffic control CPS, the embedded system is the core of sensor network node, control actuator and other equipments. It has many applications in traffic video detection devices, vehicle identity recognition, signal control devices and vehicle navigation devices, servicing for intelligent transportation systems (Sheng & Hongyu, 2012; Sehgal et al., 2010).

Cloud computing provides a scalable computing capacity for massive data. The construction of traffic cloud computing provides a platform for the fundamental data resources of transportation, software resources and computing capacity (Sheng & Hongyu 2012; Olson & Chandy, 2011). For traffic control CPS, traffic cloud computing not only satisfies the real-time ultra-large-scale computation demand for solving and simulating the complex models in the Metropolitan Transportation System Control of traffic during peak hours, but also shrinks computing capacity to adapt the simple traffic monitoring, complex data statistical analysis and traffic forecasting calculations during the night (Atzori et al., 2010), and it can meet the demands for the massive travelers to provide the computation for individual control and guidance information needed for the fine personalized traffic behavior, Such as the customized dynamic navigation route and route choice behavior control.

5. The challenges of traffic control cyber-physical systems research

Road traffic control system is one of the most complex control systems, and cyber-physical systems provides an effective theoretical approaches and solutions for traffic control problems. But the research of cyber-physical systems itself and its applications in traffic control face enormous challenges. These challenges include both transportation behavior theory, information theory, cybernetics and so on, and computing, communications, and control technologies.

The fundamental research of traffic behavior can not accurately describe the laws of individual and group traffic behavior. Traffic sensor network cannot accurately perceive traffic behavior laws automatically and the mechanism of action of behavior control theory has not been fully grasped.

Although electronic information technology and transport information technology have experienced rapid progress, but the laws of the relationship between information and human behavior cannot be accurately described. Traffic information on the effectiveness of the traffic behavior cannot be quantitatively described.

Traffic control technology development cannot meet the traffic behavior control requirements for the implementation of devices. Currently, only the traffic lights could play traffic control actuator function.

Relatively speaking, other traffic control devices are weak. Build a traffic control cyber-physical system needs to develop many new means of traffic control, such as route choice behavior control device, speed limits control devices, etc. , The development and the application of these devices involved in traffic behavior control is particularly more complex.

6. Conclusion

The road traffic is a real running physical world. However, Cyberspace is a virtual world: although information cannot independently exist without materials and energy, the information is not materials and energy. The information objectively exists in the traffic control system, and its role cannot be replaced. Traffic control cyber-physical systems integrate the information into the transportation process, and operate through their coordination, making the transportation more safe and efficient.

According to the objectives and requirements of the transportation system control, relying on automatic computing, network communication and advanced traffic control technical means and refined, coordinated and efficient configuration, scheduling, and application information to achieve both the traffic behavior control and traffic system control is worthy of further study.

Theory and design of cyber-physical systems will provide a potential solution for the problem of traffic control.

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